

# Multi-criteria selection of structural adhesives to bond ABS parts obtained by rapid prototyping

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## A B S T R A C T

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One of the most used methods in rapid prototyping is Fused Deposition Modeling (FDM), which provides components with a reasonable strength in plastic materials such as ABS and has a low environmental impact. However, the FDM process exhibits low levels of surface finishing, difficulty in getting complex and/or small geometries and low consistency in "slim" elements of the parts. Furthermore, "cantilever" elements need large material structures to be supported. The solution of these deficiencies requires a comprehensive review of the three-dimensional part design to enhance advantages and performances of FDM and reduce their constraints. As a key feature of this redesign a novel method of construction by assembling parts with structural adhesive joints is proposed. These adhesive joints should be designed specifically to fit the plastic substrate and the FDM manufacturing technology. To achieve this, the most suitable structural adhesive selection is firstly required. Therefore, the present work analyzes five different families of adhesives (cyanoacrylate, polyurethane, epoxy, acrylic and silicone), and, by means of the application of technical multi-criteria decision analysis based on the analytic hierarchy process (AHP), to select the structural adhesive that better conjugates mechanical benefits and adaptation to the FDM manufacturing process.

## 1. Introduction

The technological advances occurred in the recent years have facilitated the development of advanced systems for rapid prototyping. These techniques give physical models in a relatively short period (less than 24 h) from three-dimensional designs developed in a CAD system [1–3].

One of the most widely used techniques is the FDM since it provides ABS components with a reasonable strength and a very low environmental impact. FDM machines are clean, require little maintenance and use relatively inexpensive, odorless and non-toxic materials [4]. However, the FDM process has limitations in the surface finishing, which depends on the orientation between the XY plane and the surface. It is also difficult to set up complex or small geometries, and "slim" elements have low consistency. Finally, parts require large structures to support "cantilever" elements. All these restrictions reduce product quality and cause a significant increase in manufacturing times, costs and post-processing requirements, which limits both the range of obtainable parts (only single parts without complex interior cavity are allowed) and its scope.

Therefore, in the recent years several research works have been published (e.g., [5–8]) for improving specific attributes of parts obtained by FDM such as surface finishing or dimensional accuracy. These works modify characteristic parameters of the process, such as the thickness of each layer, orientation of the piece or structure of filling material. However, proposed modifications only have given partial improvements and have not considered an overall prototype redesign to obtain the best fit to the manufacturing process.

The solution to the deficiencies mentioned above requires a comprehensive review of part 3D-design. This allows a prototype generation enhancing FDM performances such as low environmental impact or moderate cost, and reducing limitations in macro and micro geometry. Thus, parts made by FDM will combine precision, mechanical performances and low costs, being the best alternative in comparison to other rapid prototyping processes.

As a key feature of this overall redesign a novel method of construction by assembling parts using structural adhesive joints is proposed. Joints are specifically designed to fit the plastic substrate ABS and FDM technology for manufacturing (construction using layers, dependence on construction direction, etc.). The use of adhesive joints will ease the parts redesign and will achieve the desired geometric quality with manufacturing time and cost reduction and without any loss of mechanical properties.

Adhesive bonds are used with increasing frequency in many industrial sectors, replacing or complementing traditional joining

methods such as welding or riveting. Among the benefits of structural adhesives, should be noted their high resistance, their low weight, tightness and resistance to the galvanic corrosion [9]. Therefore, adhesives are increasingly used in many manufacturing processes in various industrial sectors (aerospace, automotive, food industry, etc.). However, to obtain the inherent advantages of adhesives, their application need a specific design of the adhesive joint that enhances their performances and cut their limitations such as delicate surface preparation or reduced resistance to peel loading [10–12].

Therefore, many research papers have been made to set up analytical models of structural adhesive joints to better understand the adhesive behavior and to propose criteria for optimizing the joints design [13,14]. When the geometry of the joint is complex, many researchers have used the finite element method for simulating the behavior of the adhesive joint (e.g., [15–18]).

The integration of these works together with major contributions on design rules of structural adhesive joints [19], studies on the selection of adhesives [20,21] and geometric analysis of joints [22], allows developing a structured plan for the design of structural adhesive joints [23]. When it requires an analysis of the adequacy of structural adhesive joints in industrial production, these studies are complemented by technical and economic considerations, which assess the overall adequacy process [24,25].

This work, keeping in line with this holistic approach to adhesive joint design, in the first phase deals with the analysis and selection of the adhesive, which best combines mechanical performances and suitability to the manufacturing process FDM (dimensional quality, safety and cost of the procedure preparation). Therefore, adhesives of five different families have been analyzed: cyanoacrylate, epoxy, polyurethane, silicone and acrylic. The integration of quantitative experimental findings and the quality assessment for the process suitability in a multi-criteria decision analysis (MCDA), allows selecting the best alternative.

MCDA is a broad term that comprises many methods and techniques that are intended to assist in making complex decisions involving many aspects or attributes. The main aim is to optimize the decision as a compromise between a set of attributes, usually in conflict [26]. In this work, the technique used is based on the method of analytic hierarchy process (AHP). This technique is suitable when the number of alternatives is discrete and is based on the establishment of a hierarchical structure of the problem that supports the integration of conflicting criteria [27].

## 2. Methodology

### 2.1. Material, equipment and tools

Selection of adhesives used in the trials, has taken into account the suitability for joining ABS substrates. Moreover, they should be representative enough of one of each main families of

structural adhesives. Thus, the following adhesives have been chosen:

- Acrylics: SikaFast® 5211 adhesive by Sika.
- Polyurethane: Two component adhesive SikaForce® 7710 SikaForce® 1100 and 7010 by Sika.
- Cyanoacrylate: Loctite® 420 by Henkel.
- Epoxy: A two component adhesive Loctite® 9489 by Henkel.
- Silicone: Loctite® 5910 by Henkel.

Table 1 shows the main features of previous adhesives.

Substrates used are prismatic parts of ABS (Acrylonitrile–Butadiene–Styrene) of  $50 \times 7 \times 7$  mm obtained by FDM. The FDM machine is a Dimension BST 768 with Catalyst software and work area of  $203 \times 203 \times 305$  mm. The substrates have been built by adding ABS layers 0.2 mm thick (parallel to the XY plane) with rectangular shape  $50 \times 7$  mm, up to a height of 7 mm. In these conditions, the most relevant features of the substrates are the tensile strength (20.3 MPa in coaxial direction to the construction axis X), the elasticity modulus (1.4 MPa) and the surface roughness ( $R_a = 2.7 \mu\text{m}$ )

Due to the anisotropy of the substrate (which has a better performance to resist efforts in parallel directions into the construction plane XY) the butt joint model has been chosen to perform tensile tests with the adhesives. Fig. 1 shows the dimensions of the butt.

One of the most delicate aspects in the realization of an adhesive bond is the preparation of the substrate surface. Firstly, the surface of the joint is carefully sanded with sandpaper (grain size P600) obtaining a roughness  $R_a$  of  $2.1 \mu\text{m}$  or less. Then the substrate is cleaned with absorbent paper and hot air is applied to remove any particles attached.

An expanded polystyrene (PS) tooling has been designed and constructed in order to ensure the necessary repeatability of experiments and to keep geometric parameters invariant (thickness of adhesive and proper alignment of substrates). This tooling also serves as a support during the standing time. Fig. 2 shows the tooling used to produce the butt joints.

After the standing time the curing phase starts. At this stage it is very important to maintain the same environmental conditions (temperature and relative humidity). By cooling the room temperature has remained stable ( $25 \pm 0.4^\circ\text{C}$ ). As the relative humidity is a

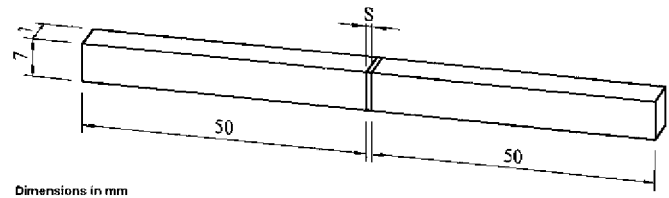


Fig. 1. Dimensions of the butt joint (mm).

**Table 1**  
Main features of selected adhesives.

Adhesive	PROPERTIES				
	Shear Strength ISO 527 (MPa)	Viscosity (mPa s)	Rest time (min)	Curing time (min)	Safety and health
Acrylic SikaFast® 5211 (bicomponent)	9	–	0.5	3	Irritant
Polyurethane SikaForce® 7710 L100 + 7010 (bicomponent)	9	10000	100	230	Mildly irritant
Cyanoacrylate Loctite® 420 (monocomponent)	15	1–5	0.1	0.25	Irritant
Epoxy Loctite® 9489 (bicomponent)	14	60,000	300	7 days	Irritant and corrosive
Silicone Loctite® 5910 (monocomponent)	1.7	–	40	20 days	Harmful

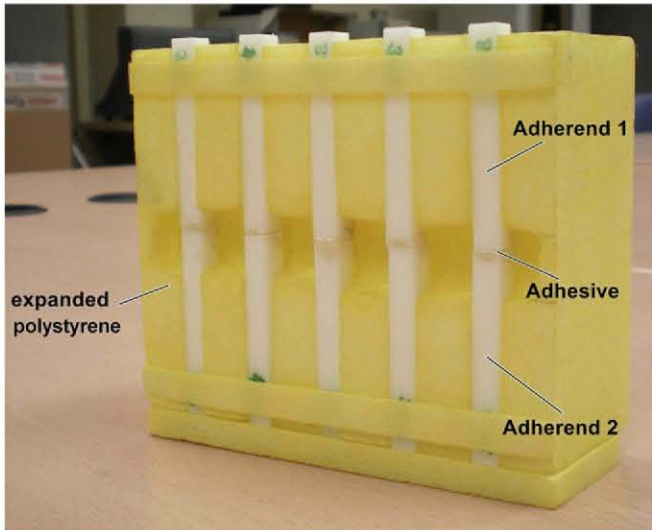


Fig. 2. Tooling by expanded polystyrene used to produce the butt joints.

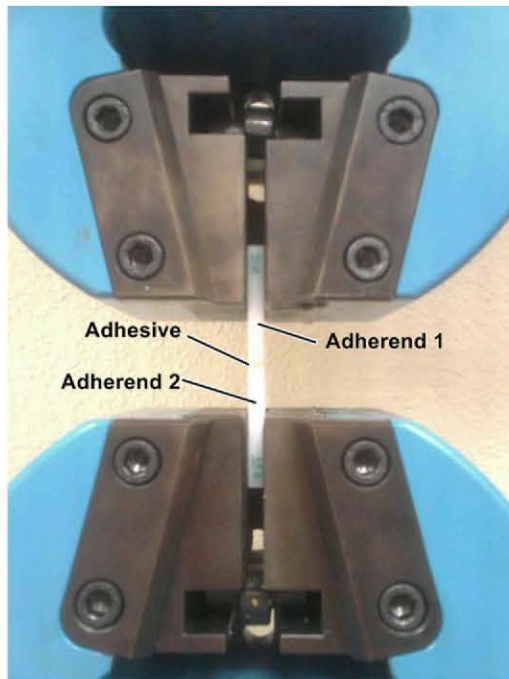


Fig. 3. Experimental set up.

critical factor in the outcome of the union, a dry chamber has been used. The chamber includes cobalt silica gel (in areas of diameters between 2 and 5 mm) and a filter to collect moisture with a saturation indicator, being chlorine free and biodegradable. The camera also includes a filter perforated support and a hygrometer for humidity control during the curing time. Inside the chamber, the relative humidity is kept between 34 and 36% during the curing period (time different for each adhesive and it is specified in Table 1).

After the curing time, the joints were removed from the chamber. A dimensional check is made with a digital calliper and the tensile test is performed. For the tensile test, a model TN-MD machine (HOYTOM, S.L., Bilbao, Spain) motorized with automatic control via computer was used (Fig. 3). Its capacity is 200 kN, the piston stroke length is 125 mm and the displacement rate was fixed at 2 mm/min.

## 2.2. Preparation of adhesive joints

Environmental conditions have been strictly controlled to reach the necessary repeatability among experiments. Temperature has been controlled by means of the lab air conditioner system and the relative humidity has been controlled by means of the homogeneous curing chamber. This will have achieved the following environmental conditions during the tests:

- Laboratory. Relative humidity:  $28 \pm 6\%$  and temperature:  $25.5 \pm 0.4$ .
- Curing chamber. Relative humidity:  $35 \pm 1\%$  and temperature:  $26 \pm 1$  °C.

The polystyrene tooling allows obtaining adhesive joints with the desired adhesive thickness and also facilitates the proper alignment of the substrates. Lower substrate receives the adhesive by a manual dispenser and then, the second substrate is wiped over it. Once the assembly is ready, the excess adhesive is wiped off to avoid possible sources of fracture, and the whole joint remains at rest during the specified time in the adhesive data sheet. During the standing time a weight of 200 g is placed at the top of the tool to obtain adequate pressure on the substrates. After this time, joints are placed in the chamber for uniform curing of the adhesive bond cured at this corresponding time.

## 2.3. Tensile test

Experimental procedure carries on 10 tensile test for each considered adhesives (acrylic, cyanoacrylate, polyurethane, epoxies and silicones) in keeping with the procedure described in the UNE-EN 15870 on the determination of tensile strength of butt joints [28].

## 3. Results

In all trials, load-displacement curves have been approximately linear until failure. As an example, Fig. 4 shows the tensile stress-strain curve and the failure surface for one of the butt joints made with two-component polyurethane adhesive Sika.

Table 2 shows the figures obtained for tensile strength ( $\sigma$ : failure load/surface binding) and the failure mode for each adhesive. Fig. 5 shows a graph of the variation in tensile strength (in MPa) according to the adhesive used. The analysis of this figure leads to the following results:

- (a) Loctite 420 cyanoacrylate gives the highest average value of the tensile strength (12.67 MPa) although its variation range is also the highest (5.23 MPa).
- (b) Acrylic adhesives (SikaFast 3201) and polyurethanes (7710 SikaForce L100+7010) have similar figures for average tensile strength (8.92 MPa and 8.12 MPa, respectively) both lower than cyanoacrylate. Acrylic range is lower than the polyurethane range (1.59 MPa versus 2.87 MPa).
- (c) Epoxy adhesives (Loctite 9489) and silicone (Loctite 5910) have low figures for average stress fracture (5.45 and 1.37 MPa, respectively) and relatively low ranges (2.27 and 0.79 MPa, respectively).

Moreover, dimensional control carried out after curing time of adhesive joints has shown adequate dimensional accuracy in all assemblies except for that made with cyanoacrylate. In this case, the adhesive has chemically attacked the substrate causing a slight irregular solution of the outermost layer (decrease between 0.1 and 0.2 mm) altering the geometry of the joint.



#### 4. Adhesives analysis and selection

The analysis carried out over tensile strength and over the range of adhesive joints is not enough to assess their suitability of application in rapid prototyping. From the manufacturing point of view the consideration of other important factors is also required, such as the speed of collection, the safety and the associated costs, among others.

In this sense, the use of a multi-criteria decision system based on the method of analytic hierarchy (AHP) is an appropriate tool. It allows the choice of the most appropriate adhesive for joining ABS parts. This method is based on the establishment of a hierarchical structure of the problem and is suitable for working with a series of information integrating quantitative data (voltage, time) and qualitative criteria (safety, method of execution) to select the best alternative.

The main steps to be followed in a multi-criteria decision-making process are: (a) analysis of alternatives, (b) selection of decision criteria, (c) weighting of criteria, (d) the assessment of

alternatives according to each criterion, (e) calculating the gain or global priority of each alternative and (f) results analysis.

The following have been the decision criteria taken into account in order to choose an adhesive: technological criteria (resistance of the joint, adaptation to the substrate, etc.), suitability of the adhesive to the FDM process (health and safety in the process, time of execution, etc.) and economic criteria. In order to organize the prior criteria in levels and sublevels a hierarchical breakdown of the same in accordance with the AHP method has been carried out. The classification obtained is the following:

1. *Selection of the best adhesive (level 1).* The selection of the adhesive is based on the following criteria:

1.1. *Technological criterion (level 2).* This takes into account the technical performance achieved by each adhesive. This approach can be divided into the following subheadings (level 3):

1.1.1. *Joint strength (maximize).* Quantitative criterion specified by the mean stress at fracture in tension (in MPa) obtained in the tests.

1.1.2. *Adaptation to the substrates (maximize).* Qualitative criterion that assesses the interaction between adhesive and substrate. It takes into account both the percentage of cohesive failure as the degree of chemical alteration that may occur to the substrate by action of the adhesive.

1.1.3. *Dispersion or variation in the adhesive bond (minimize).* Quantitative criterion based on the ratio "range/mean stress at break" to estimate the degree of centrality of the values of stress in the adhesive joint.

1.2. *Suitability to the process (level 2).* This criterion assesses the usefulness of the adhesive to meet FDM requirements such as speed of production, processing techniques office or

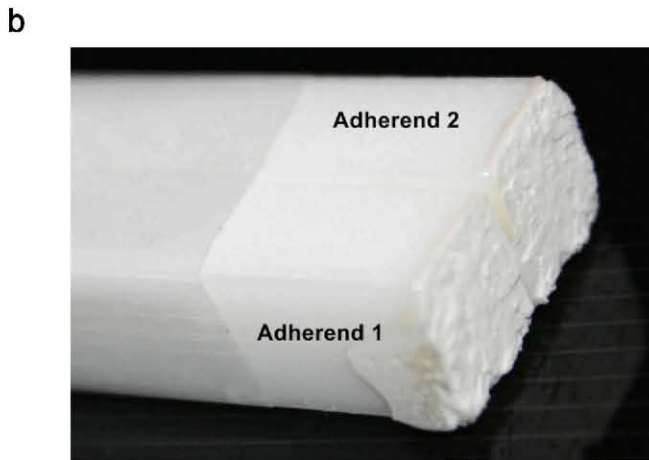
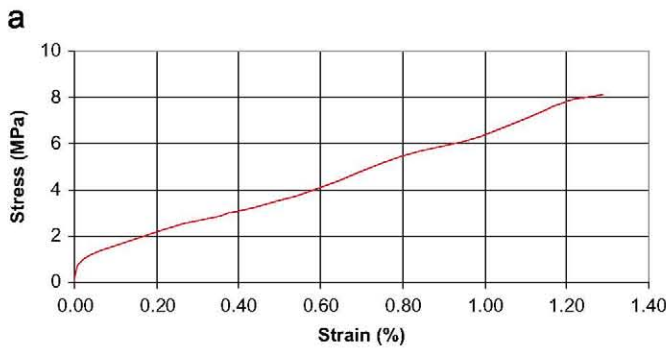


Fig. 4. Tensile stress-strain curve (a) and failure surface (b) for one of the butt joints made with polyurethane adhesive.

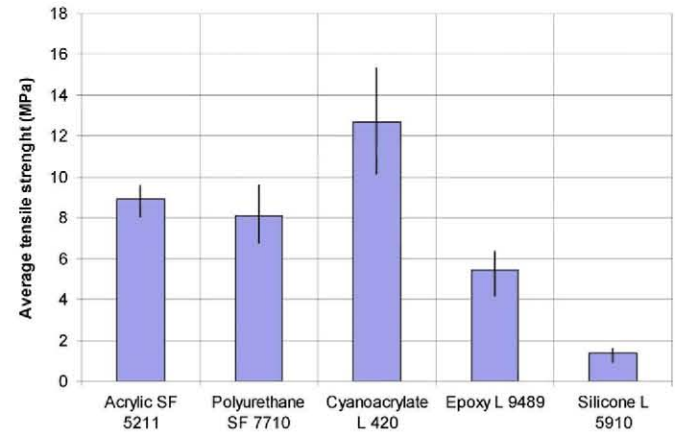


Fig. 5. Average tensile strength (in MPa) of each adhesive type.

Table 2  
Tensile strength values and type of failure for each adhesive.

Adhesive	Thickness Adhesive (mm)	Tensile strength $\tau$ (MPa)				Failure mode (%)		
		Mean	Max.	Min.	Standard Deviation	Cohesive	Mixed	Adhesive
Acrylic SikaFast® 5211	1	8.92	9.63	8.04	0.56	30	50	20
Polyurethane SikaForce® 7710 L100 + 7010	0.5	8.12	9.65	6.78	0.83	70	20	10
Cyanoacrylate Loctite® 420	0.1	12.67	15.41	10.18	1.85	60	40	0
Epoxy Loctite® 9489	0.2	5.45	6.43	4.16	0.79	0	40	60
Silicone Loctite® 5910	1	1.37	1.69	0.90	0.23	0	70	30

limited production runs. This approach can be divided into the following subheadings (*level 3*):

- 1.2.1. *Process safety* (maximize). Qualitative criterion that assesses the performance of an adhesive to be used in a clean environment (such as technical office), the required security requirements and the extent to which they affect human health (irritant, toxic, etc.).
- 1.2.2. *Runtime adhesive bonding* (minimize). Quantitative criterion that assesses the total time needed for the adhesive joint execution, including preparation time, rest time, curing time, etc.
- 1.2.3. *Adhesive preparation and application* (maximize). Qualitative criterion that assesses the ease of preparing the adhesive in the technical office: tools needed to prepare the mixture, method of adhesive application, etc.
- 1.3. *Economic criterion* (*level 2*). This covers the economic aspects of adhesive bonding and quantitatively measures the cost of adhesive materials and labor required.

Relative importance of each criterion in relation to the other is expressed by weighting the criteria. Once the ranking of the decision criteria is completed, binary comparisons are made between the selection criteria of each level. These comparisons are based on the importance for each criterion with respect to top-level criteria that are linked. The comparison process leads to a scale to measure relative priorities or weights of the elements. Criteria weights are calculated in each hierarchical level by comparing them two by two, considering whether criterion  $C_i$  is better than  $C_j$  (or vice versa) and how much better. To do this, the scale proposed by Saaty et al. [27] is used:

$C_{ij}=1$ : same importance between criteria  $i$  and  $j$ ;  
 $C_{ij}=3$ : criterion  $i$  slightly more important than criterion  $j$ ;  
 $C_{ij}=5$ : criterion  $i$  more important than criterion  $j$ ;  
 $C_{ij}=7$ : criterion  $i$  far more important than criterion  $j$ ;  
 $C_{ij}=9$ : criterion  $i$  absolutely most important than the criterion  $j$ .

Table 3 shows the application of this process in the hierarchical level 2. The level 2 criteria are as follows: technological criteria, suitability to the process and economic criteria. These criteria are compared two by two hereunder and they are analyzed in order to decide, which is the most important for the selection of the best adhesive in the manufacturing of parts using FDM. Thus, the following binary comparisons are obtained:

- “Technological criteria” is slightly more important than “suitability for the process”. If the “technological criteria” is regarded as number 1 and the “suitability for the process” as number 2, the application of the Saaty scale implies  $C_{12}=3$ . Therefore, in Table 3 the intersection cell with the second column has the value of 3. The inverse comparison (“suitability for the process” is slightly less important than the “technological criteria”) similarly implied

$C_{21}=1/3$  and the intersection cell of the second line with the first column has the value of  $1/3$ .

- “Technological criteria” is absolutely more important than the “economic criteria”. If the “economic criteria” is regarded as number 3, the application of the Saaty scale implied  $C_{13}=9$ . Therefore, in Table 3 the intersection cell of the first line with the third column has the value of 9. The inverse comparison (“economic criteria” is considerably less important than the “technological criteria” similarly implying  $C_{31}=1/9$  and the intersection cell of the third line with the first column has the value of  $1/9$ .
- “Suitability for the process” is slightly more important than the “economic criteria”. In this case, the application of the Saaty scale implies  $C_{23}=3$ . Therefore, in Table 3 the intersection cell of the second line with the third column has the value of 3. The inverse comparison (“economic criteria”) is slightly less important than the “adaptation to the process”, similarly implying  $C_{32}=1/3$  and the intersection cell of the third line with the second column has the value of  $1/3$ .

The weightings or weights ( $W_i$ ) of each selection criteria (technological criteria, suitability for the process and economic criteria) indicate the relative importance of each criteria with regards to the others. The relative weights  $W_i$  are calculated as from the data  $C_{ij}$  of Table 3. Therefore, the validity of the relative weights will depend on the coherence and correction of the data  $C_{ij}$  included in Table 3. The quantitative analysis of the coherence and correction of the comparisons carried out (data  $C_{ij}$ ) is called assessment of the degree of consistency of the value judgements carried out in binary comparisons. In the AHP method the relative weights  $W_i$  have to be calculated, as well as the degree of consistency of the value judgements. Therefore, a mathematical solution is proposed, based on the programming by weighted targets including two new variables ( $n_i \geq 0$  and  $p_i \geq 0$ ) for each relative weight, which allow calculating the degree of consistency of the value judgements. For example, when it is decided that the coefficient  $C_{12}$  of Table 2 has to take a value of 3, this means that it has been estimated that  $W_1$  is  $3W_2$ . However, there is no certainty that this estimation is exact although it is quite sure that  $W_1$  will be the same or higher than  $3W_2$  (specifically,  $p_1$ ) or the same or less than  $3W_2$  (specifically,  $n_1$ ). That is to say, the following will be complied with:

$$W_1 + n_1 - p_1 = 3W_2 \quad (1)$$

In the resolution of Eq. (1) it cannot be simultaneously  $n_1 > 0$  and  $p_1 > 0$  as  $W_1$  cannot be higher and lower than  $3W_2$  at the same time. Therefore, if  $n_1 > 0$  then  $p_1 = 0$  and, vice versa, if  $p_1 > 0$  it should be  $n_1 = 0$ . However, it can happen at the same time that  $n_1 = 0$  and  $p_1 = 0$ ; in this case the decision taken when considering  $C_{12}=3$  has been exactly as  $W_1=3W_2$ .

Therefore, the variables  $n_i$  and  $p_i$  allow calculating the degree of consistency of the judgement values emitted on the coefficients  $C_{ij}$ . The lower the values obtained for variables  $n_i$  and  $p_i$  the higher the degree of consistency of the judgement values (the estimation of the coefficients  $C_{ij}$  will have been more correct, and, therefore, the relative weights calculated as from these coefficients will be more exact).

Applying the prior considerations to the data  $C_{ij}$  of Table 3 the following equations are obtained:

$$\begin{aligned} W_1 - 3W_2 + n_1 - p_1 &= 0 \\ W_1 - 9W_3 + n_2 - p_2 &= 0 \\ W_2 - 3W_3 + n_3 - p_3 &= 0 \\ W_1 + W_2 + W_3 &= 1 \\ W_1 \geq 0; W_2 \geq 0; W_3 \geq 0 \\ \text{Min}(n_1 + p_1 + n_2 + p_2 + n_3 + p_3) & \end{aligned} \quad (2)$$

**Table 3**  
Weights of criteria for hierarchical level two.

	Technological criterion	Adjustment to the process	Economic criterion	Weight ( $W_i$ )
Technological criterion	1	3	9	0.692
Adjustment to the process	1/3	1	3	0.231
Economic criterion	1/9	1/3	1	0.077

where:  $W_1$ ,  $W_2$  and  $W_3$  are the weightings of each selection criteria;  $n_1$ ,  $n_2$  and  $n_3$  are the deviation variables by defect of  $W_1$ ,  $W_2$  and  $W_3$ ;  $p_1$ ,  $p_2$  and  $p_3$  are the deviation variables by excess of  $W_1$ ,  $W_2$  and  $W_3$ .

The first three equations of the system (2) are deduced immediately from the coefficients  $C_{ij}$  of Table 3, the fourth and fifth equations consider the typical characteristics of the relative weights and the sixth equation is introduced in order to minimize the addition of the deviation variables (the objective is to obtain the highest degree of consistency in the judgement values).

The algorithmic structure of the equation system (2) corresponds to a linear programming model, which can be resolved using the Simplex method. The use of specific software (GIPAL v. 3.1.0) yield the following solution:  $W_1=0.692$ ,  $W_2=0.231$ ,  $W_3=0.077$  and  $n_1=n_2=n_3=p_1=p_2=p_3=0$ .

The void value obtained for the objective function (Min  $n_1+p_1+n_2+p_2+n_3+p_3$ ) means that the degree of consistency of the judgement values carried out in the binary comparisons has been excellent.

It is noted that the technological criterion (0.692) is the most valued, followed by the process fitness (0.231). In this case, the economic criterion is not very relevant (0.077) as the rapid prototyping production runs are usually small and the impact of their cost on the total FDM manufacturing cost of a part is moderated.

Following the same procedure the criteria weights at hierarchical level 3 are obtained (Tables 4 and 5). Table 6 summarizes these results and shows the hierarchical structure of the selection process with the criteria arranged in three levels and their corresponding weights.

Once the selecting criteria weights are determined, alternatives are assessed according to each criterion. For this purpose, value judgments are shown when each adhesive is confronted with each criterion. If the criteria are quantitative (average voltage, time, etc.) the numerical rating preferences scale is transformed in a linear way. If the criteria are qualitative (safety and health, adaptation to the substrate, etc.) comparison matrices are produced by pairs of adhesives for each criterion. Tables 7–9

**Table 4**  
Weights of subcriteria for technological criterion.

	Joint strength	Adaptation to the substrates	Dispersion	Weight (W)
Joint strength	1	3	7	0.677
Adaptation to the substrates	1/3	1	3	0.226
Dispersion	1/7	1/3	1	0.097

**Table 5**  
Weights of criteria for adjustment criterion to the FDM process.

	Safety and health	Runtime adhesive bonding	Preparation and application	Weight (W)
Safety and health	1	3	9	0.692
Runtime adhesive bonding	1/3	1	3	0.231
Preparation and application	1/9	1/3	1	0.077

show these matrices for comparing the qualitative criteria and their corresponding weights (also obtained using a model of weighted goal programming).

Table 10 shows the weights obtained for each adhesive and each criterion. Quantitative criteria display the corresponding numerical value in brackets (obtained in the test or calculated).

Table 11 shows the final priority or utility matrix of each adhesive (the weights appear in brackets). Utility is calculated using a multiplicative aggregation between hierarchical levels. Thus, for acrylic assessing, the suitability of the substrate is obtained as follows:  $0.692 \times 0.226 \times 0.296 = 0.046$ . Total utility of acrylic adhesive is calculated by adding all values in each column (0.255).

Fig. 6 shows the total utility (in %) of each adhesive. From the figure it appears that the most suitable adhesive for bonding parts obtained by FDM rapid prototyping is the two-component polyurethane (L100 SikaForce® 7710 & 7010), which has a 29.2% profit. Additionally, the acrylic adhesive SikaFast 5211 can also be considered as an alternative option (utility 25.5%) so it has a good performance in the most relevant criteria (resistance, adaptation to the substrate, safety and health). The use of cyanoacrylate is not recommended. Although it has a utility of 23.9%, it has a major deficiency in a relevant aspect for the FDM process (partial dissolution of the substrate). At any rate, the use of epoxy and silicone (profits of 12.3% and 7.4%, respectively) should be discarded because they show a very low performance in most criteria.

## 5. Conclusions

One of the most widely used methods in rapid prototyping is the Fused Deposition Modeling (FDM), which provides components with a reasonable strength in plastic materials such as ABS and has a low environmental impact. However, FDM process exhibits low levels of surface finishing, difficult in obtaining complex and/or small geometries and low consistency in “slim” elements of the parts. Furthermore, “cantilever” elements need large material structures to be supported. The solution of these deficiencies requires a comprehensive review of the three-dimensional part design to enhance advantages and performances of FDM and reduce their constraints. As a key feature of this redesign a novel method of construction by assembling parts with structural adhesive joints is proposed. These parts must be specifically designed to fit the plastic substrate and the FDM technology for manufacturing (construction using layers, mechanical properties dependent on the constructive leadership, etc.).

To achieve this, it firstly requires the most suitable structural adhesive selection. Therefore, the present work analyzes adhesives of five different families (cyanoacrylate, polyurethane, epoxy, acrylic and silicone). Although the experimental test on shear stress of butt joint advise the use of cyanoacrylate, the application of technical multi-criteria decision analysis based on the analytic hierarchy process (AHP), which values combined and pondered mechanical benefits and adaptation to FDM manufacturing process, has led us to select polyurethane as a better adhesive and acrylic as a second option. In any event, the analysis has discarded to use cyanoacrylate, epoxy and silicone.

Therefore, the procedure described in this work has led us to choose the best structural adhesive to bond pieces of ABS obtained by FDM but also it has shown the suitability of the application of techniques of multi-criterion decision (AHP) in problems of selection in structural adhesion field where the combined valuation of technical and economic criteria and adaptation to the manufacturing process is required.

**Table 6**  
Hierarchical structure of the selection criteria and corresponding weights.

Level 1	Level 2	Level 3
Selection of the best adhesive (1)	Technological criterion (0.692)	Joint strength (0.677)
	Adjustment to the FDM process (0.231)	Adaptation to the substrates (0.226)
		Dispersion (0.097)
		Safety and health (0.692)
Economic criterion (0.077)		Runtime adhesive bonding (0.231)
		Preparation and application (0.077)
		Manufacturing cost (1)

**Table 7**  
Comparison matrix for adaptation criterion to the substrates.

	Polyurethane SikaForce 7710-7010	Acrylic SikaFast 5211	Silicone Loctite 5910	Cyanoacrylate Loctite 420	Epoxy Loctite 9489	W
Polyurethane SikaF. 7710	1	3	5	7	9	0.493
Acrylic SikaFast 5211	1/3	1	3	5	7	0.296
Silicone Loctite 5910	1/5	1/3	1	3	5	0.099
Cyanoacrylate Loctite 420	1/7	1/5	1/3	1	3	0.070
Epoxy Loctite 9489	1/9	1/7	1/5	1/3	1	0.042

**Table 8**  
Comparison matrix for application criterion of the adhesive.

	Cyanoacrylate Loctite 420	Epoxy Loctite 9489	Silicone Loctite 5910	Acrylic SikaFast 5211	Polyurethane SikaForce 7710-7010	W
Cyanoacrylate Loctite 420	1	3	5	7	9	0.493
Epoxy Loctite 9489	1/3	1	3	5	7	0.296
Silicone Loctite 5910	1/5	1/3	1	3	5	0.099
Acrylic SikaFast 5211	1/7	1/5	1/3	1	3	0.070
Polyurethane SikaF. 7710	1/9	1/7	1/5	1/3	1	0.042

**Table 9**  
Comparison matrix for safety and health criterion.

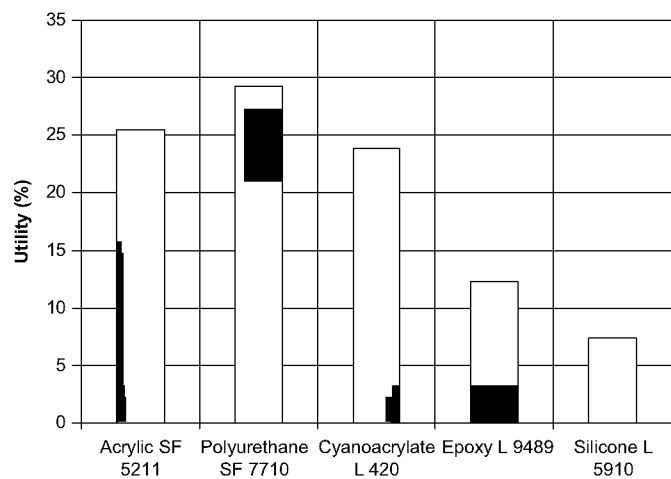
	Polyurethane SikaForce 7710-7010	Acrylic SikaFast 5211	Cyanoacrylate Loctite 420	Epoxy Loctite 9489	Silicone Loctite 5910	W
Polyurethane SikaF. 7710	1	3	5	7	9	0.493
Acrylic SikaFast 5211	1/3	1	3	5	7	0.296
Cyanoacrylate Loctite 420	1/5	1/3	1	3	5	0.099
Epoxy Loctite 9489	1/7	1/5	1/3	1	3	0.070
Silicone Loctite 5910	1/9	1/7	1/5	1/3	1	0.042

**Table 10**  
Weight of each adhesive regarding each selection criterion.

LEVELS			ALTERNATIVES				
1	2	3	Acrylic SikaFast 5211	Polyurethane SikaForce 7710-7010	Cyanoacrylate Loctite 420	Epoxy Loctite 9489	Silicone Loctite 5910
Selection of the best adhesive <b>1</b>	Technological criterion <b>0.692</b>	Joint strength 0.677 (MPa)	0.244 (8.92)	0.222 (8.12)	0.347 (12.67)	0.149 (5.45)	0.038 (1.37)
		Adaptation to the substrates 0.226	0.296	0.493	0.070	0.042	0.099
		Dispersion 0.097 (Range/str.)	0.269 (17%)	0.210 (35%)	0.191 (41%)	0.191 (41%)	0.139 (57%)
	Adjustment to the FDM process <b>0.231</b>	Safety and health 0.692	0.296	0.493	0.099	0.070	0.042
		Runtime adhesive bonding 0.231 (time in h)	0.249 (0.5)	0.239 (4.7)	0.250 (0.18)	0.073 (76)	0.189 (26)
		Preparation and application 0.077	0.070	0.042	0.493	0.296	0.099
	Economic criterion <b>0.077</b>	Manufact. cost 1 (Cost: €)	0.210 (0.23)	0.097 (0.9)	0.243 (0.04)	0.233 (0.1)	0.216 (0.2)

**Table 11**  
Final matrix of utility for each adhesive.

LEVELS			ALTERNATIVES				
1	2	3	Acrylic SikaFast 5211	Polyurethane SikaForce 7710-7010	Cyanoacrylate Loctite 420	Epoxy Loctite 9489	Silicone Loctite 5910
Selection of the best adhesive <b>1</b>	Technological criterion <b>0.692</b>	Joint strength (0.677)	(0.244) 0.114	(0.222) 0.103	(0.347) 0.162	(0.149) 0.069	(0.038) 0.017
		Adaptation to the substrates (0.226)	(0.296) 0.046	(0.493) 0.077	(0.070) 0.011	(0.042) 0.006	(0.099) 0.015
		Dispersion (0.097)	(0.269) 0.018	(0.210) 0.014	(0.191) 0.012	(0.191) 0.012	(0.139) 0.009
		Adjustment to the FDM process <b>0.231</b>	(0.296) 0.047	(0.493) 0.078	(0.099) 0.015	(0.070) 0.011	(0.042) 0.006
	Economic criterion <b>0.077</b>	Safety and health (0.692)	(0.249) 0.013	(0.239) 0.012	(0.250) 0.013	(0.073) 0.003	(0.189) 0.010
		Runtime adhesive bonding (0.231)	(0.070) 0.001	(0.042) 0.001	(0.493) 0.008	(0.296) 0.005	(0.099) 0.001
		Preparation and application (0.077)	(0.211) 0.016	(0.097) 0.007	(0.243) 0.018	(0.233) 0.017	(0.216) 0.016
		Manufact. cost (1)					
		<b>TOTAL</b>	<b>0.255</b>	<b>0.292</b>	<b>0.239</b>	<b>0.123</b>	<b>0.074</b>



**Fig. 6.** Utility of each adhesive.

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